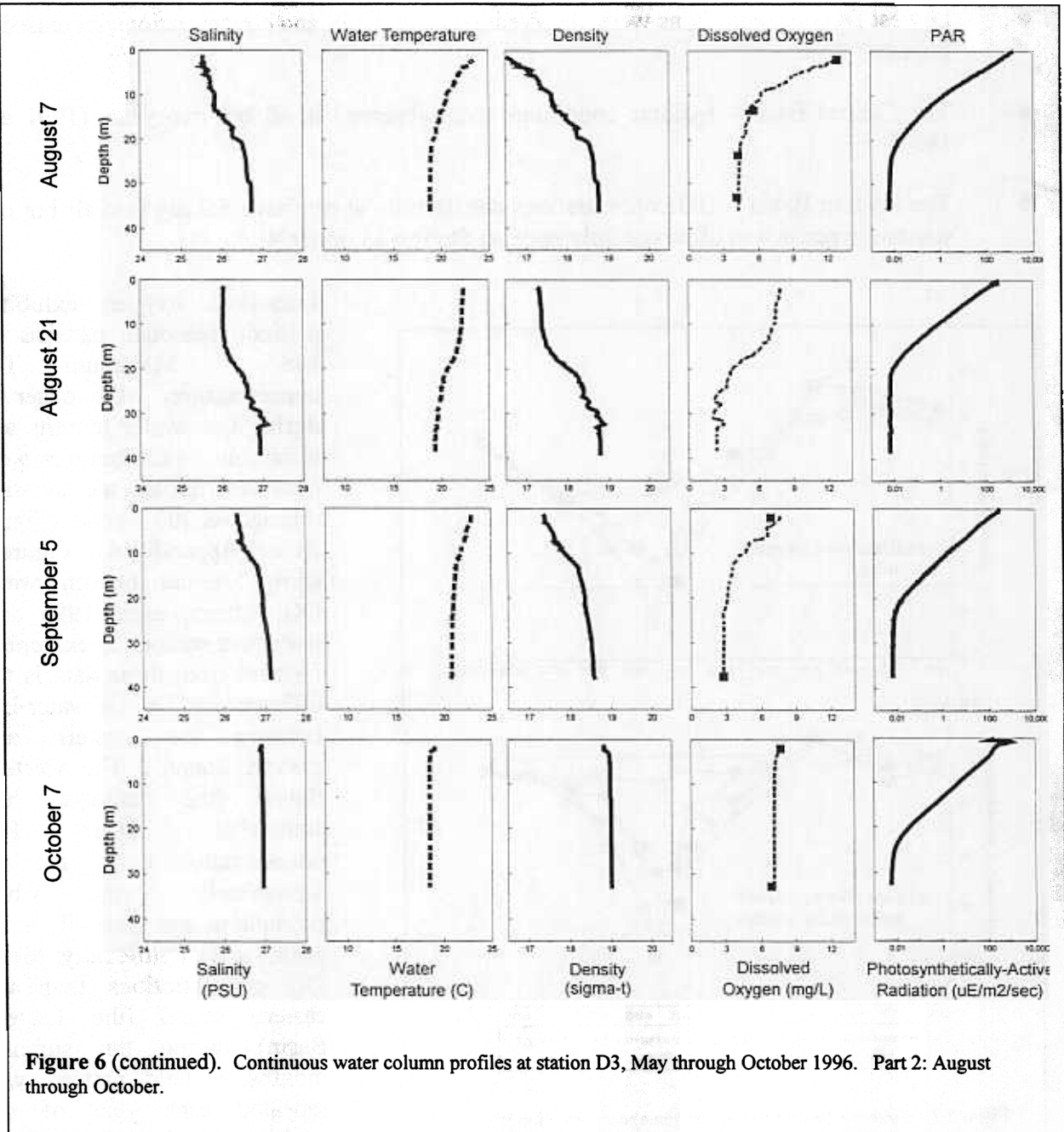
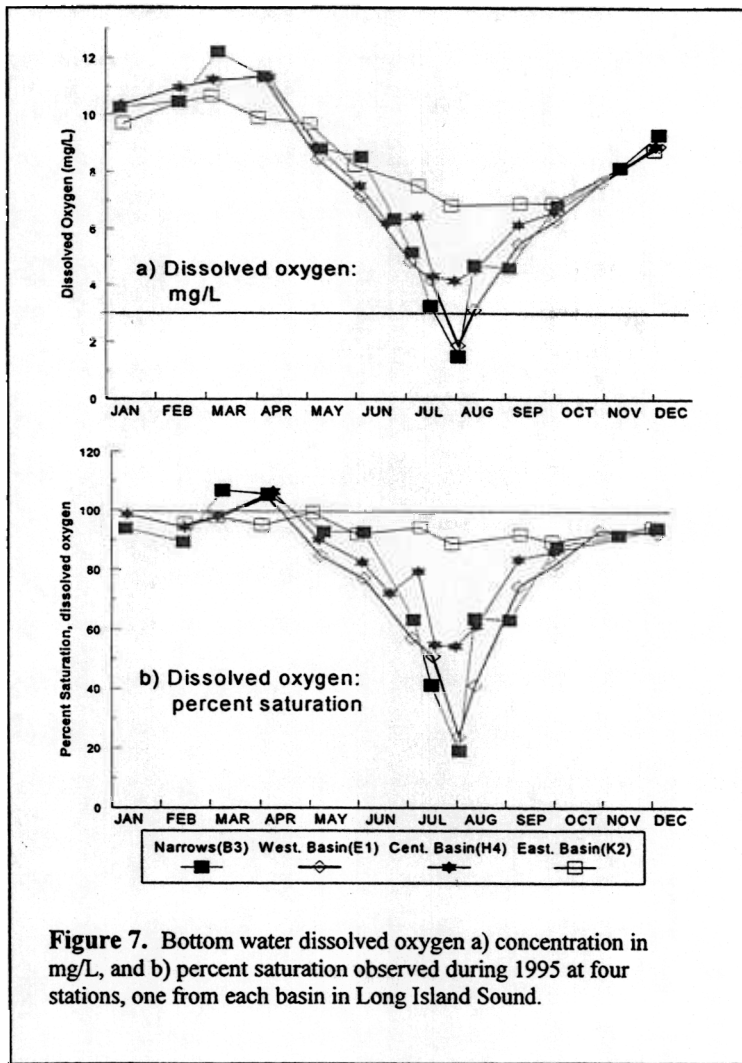


**Figure 6.** Continuous water column profiles at station D3, May through October 1996. Part 1: May through July. "■" shows the result of chemical titrations for dissolved oxygen on discrete water samples plotted over CTD profiling results.



- Lowest DO concentrations of the year were most often observed during August
- Maximum area of hypoxia was observed during August in all but one year (1998)
- The Narrows - hypoxic conditions were observed every year
- The Western Basin - hypoxic conditions were observed in all but one year (1997)

- Lowest DO concentrations were observed in western LIS and concentrations increased to the east
- The Central Basin - hypoxic conditions were observed in all but two years (1991 and 1997)
- The Eastern Basin – DO concentrations consistently at or above 5.2 mg/L at all but one station; hypoxia was observed only once, at Station 33, in 1994



**Figure 7.** Bottom water dissolved oxygen a) concentration in mg/L, and b) percent saturation observed during 1995 at four stations, one from each basin in Long Island Sound.

Dissolved oxygen exhibited distinct seasonal patterns in LIS. Maximum DO concentrations were observed during the winter months and minimum concentrations were observed during the summer throughout the Sound (Figure 7a and Appendix A). Figure 7 shows annual bottom water DO patterns using 1995 data from four stations as examples. Evident from these data is the difference in bottom water DO between the western and eastern Sound. The western Sound (the Narrows) had somewhat higher DO concentrations during the late winter/early spring, when production was generally at its peak, and significantly lower DO concentrations than the eastern sound (the Eastern Basin) during the summer months. This pattern was repeated each year of the study. During the winter months concentrations of DO in both surface and bottom waters were near or above 100% saturation (Figure 7b).

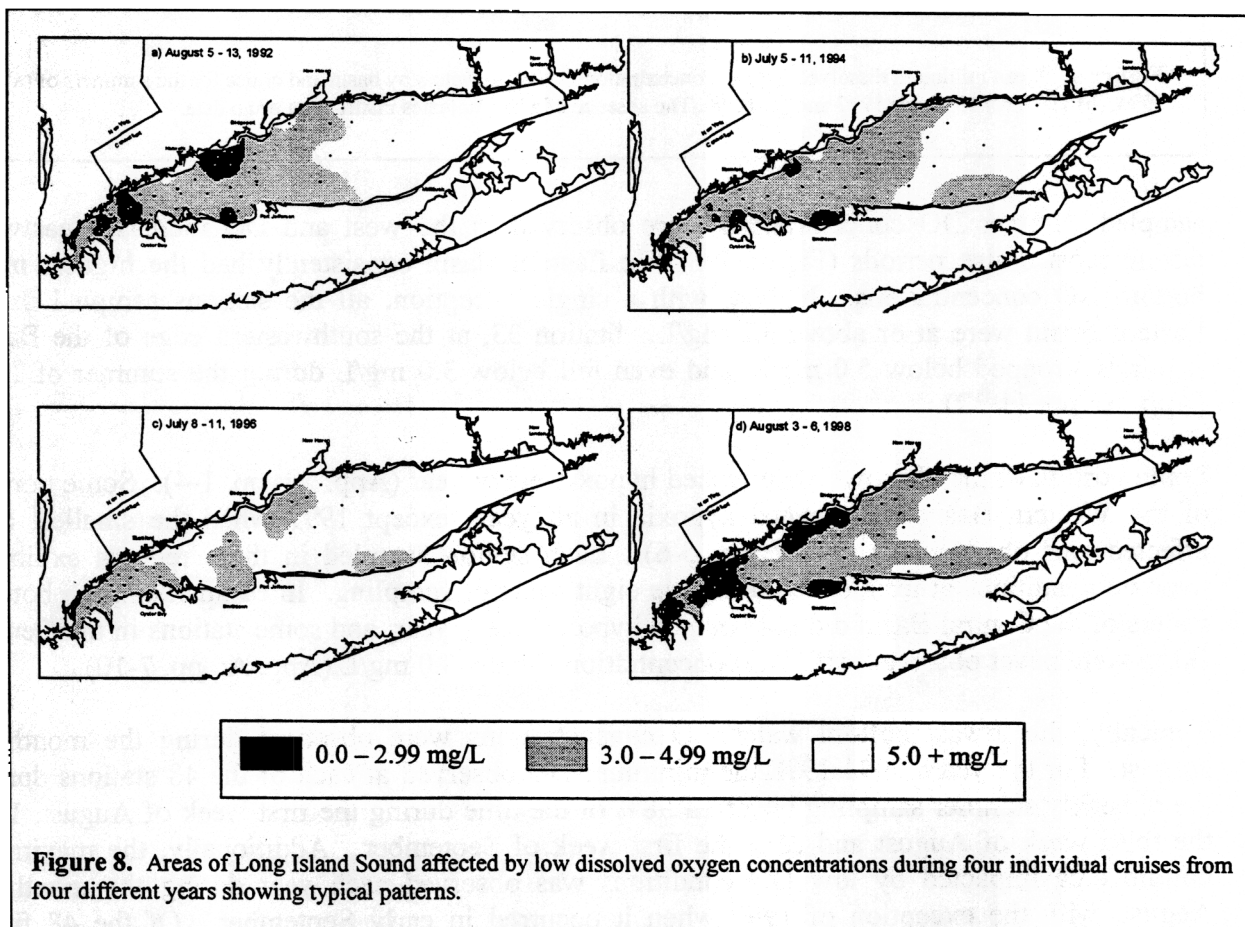
During the summer months percent saturation generally declined, especially in the bottom waters of the western and central Sound (Figure 7b).

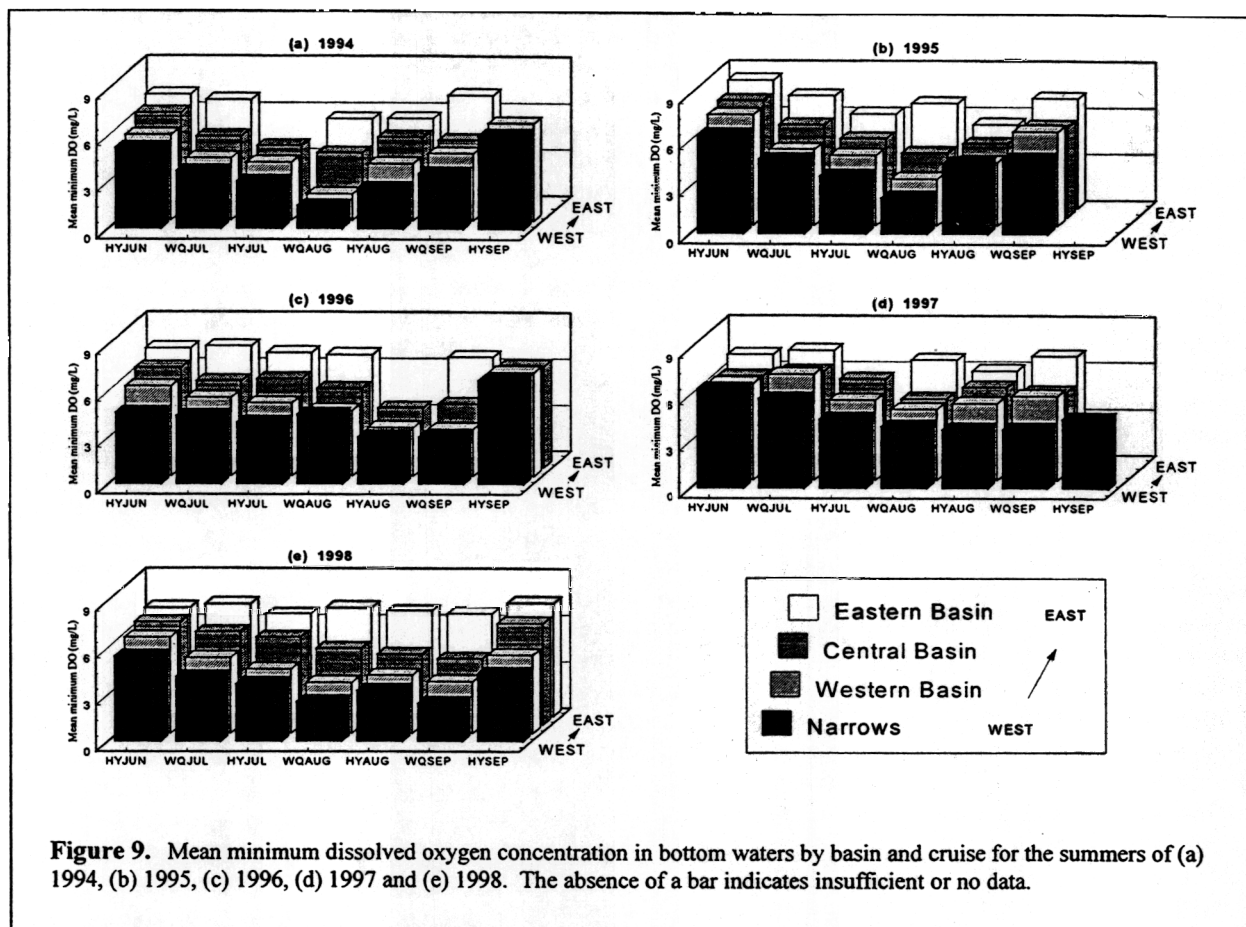
The annual range in bottom water DO concentrations was larger at western stations than at eastern stations. Higher levels of nutrients in the western Sound support higher phytoplankton

production and higher DO concentrations during the late winter/early spring bloom. Most of the difference in annual DO range between the western and eastern Sound however, is a result of the extreme difference between the summer lows. Stronger thermal stratification and larger organic loads delivered to the bottom waters in the west result in significant declines in DO concentration in the bottom waters there.

In general, DO concentrations were lowest in the bottom waters of the Narrows and Western Basin and improved eastward. Although this pattern holds true for the axial (deep-water) portion of LIS, the shallower areas frequently had lower DO concentrations during the summer period, especially in the Central Basin. Figure 8 shows the tendency for lower DO to develop in the shallower waters along the northern and southern boundaries of the Sound. Depth, however, was not the singular factor in the development of low dissolved oxygen conditions. Hypoxia was observed at stations that ranged in depth from shallow (less than 10 meters) to deep (greater than 40 meters). Location within LIS was more consistently related to the occurrence of low DO than depth. In general, the farther west the station, the greater likelihood for lower DO.

Stations in the Narrows and Western Basin of LIS generally had lower mean DO concentrations in the bottom waters throughout the summer than the Central and Eastern Basin stations (Figure 9). A mean was calculated for each basin using the minimum DO observed at each station

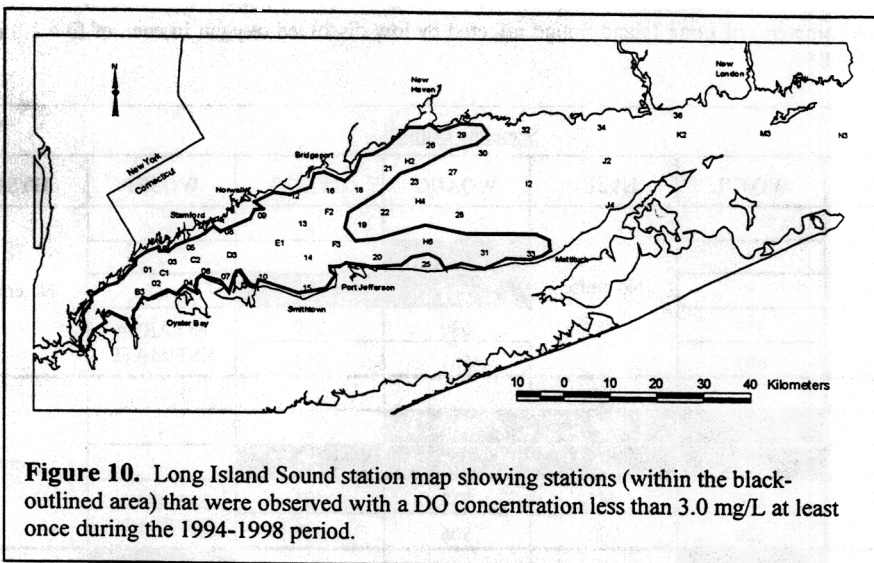




sampled. Lower DO concentrations were observed in the west and DO increased eastward during most cruise periods (Figure 9). The Eastern Basin consistently had the highest mean bottom DO concentrations. In fact, with a single exception, all the stations sampled in the Eastern Basin were at or above 5.2 mg/L. Station 33, at the southwestern edge of the Basin, regularly dropped below 5.0 mg/L, and even fell below 3.0 mg/L during the summer of 1994 (App. A: pp. 11-12).

Some portion of the Narrows experienced hypoxia every year (App. A: pp. 1-4). Some portion of the Western Basin experienced hypoxia in all years except 1997 when the smallest area affected was observed (App. A: pp. 5-6). Each station sampled in these regions exhibited hypoxic conditions at least once during the eight years of sampling. In comparison, the bottom waters of the Central Basin did not become hypoxic every year, and some stations in the Central Basin were never observed with DO concentrations below 3.0 mg/L (App. A: pp. 7-10).

Typically, the lowest bottom water DO concentrations were observed during the month of August. For the years 1994-1998 the minimum DO observed at each of the 48 stations during the biweekly summer sampling occurred 58% of the time during the first week of August, 17% the third week of August and 25% the first week of September. Additionally, the maximum bottom area impacted by low DO conditions was observed each year during the month of August, with the exception of 1998 when it occurred in early September. Of the 48 fixed



sampling stations (1994-1998), thirty-two became hypoxic at least once during the five-year period (Figure 10). Of these 32 stations, five had minimum observed DO concentrations of less than 1.0 mg/L; eleven had minimum observed DO between 1.0 and 1.99 mg/L; the remaining sixteen stations had

minimum observed DO between 2.0 and 2.99 mg/L. Many of the minimum DO concentrations observed occurred during the summer of 1994 (cruise WQAUG94 in particular) when hypoxia was especially severe.

### *Summary of Summer Conditions by Year*

#### **1991**

In the summer of 1991, four cruises were conducted between July 8 and September 12. The first sampling period was July 8 to July 18 (WQJUL91). In this period the minimum bottom water dissolved oxygen concentration observed was 3.1 mg/L in the Narrows. Although no hypoxia was observed at this time, the area with DO concentrations less than 5.0 mg/L was widespread, covering an area of approximately 960 square kilometers (km<sup>2</sup>) encompassing most of the Narrows and Western Basin and a portion of the Central Basin (Table 5 and pp. C-1).

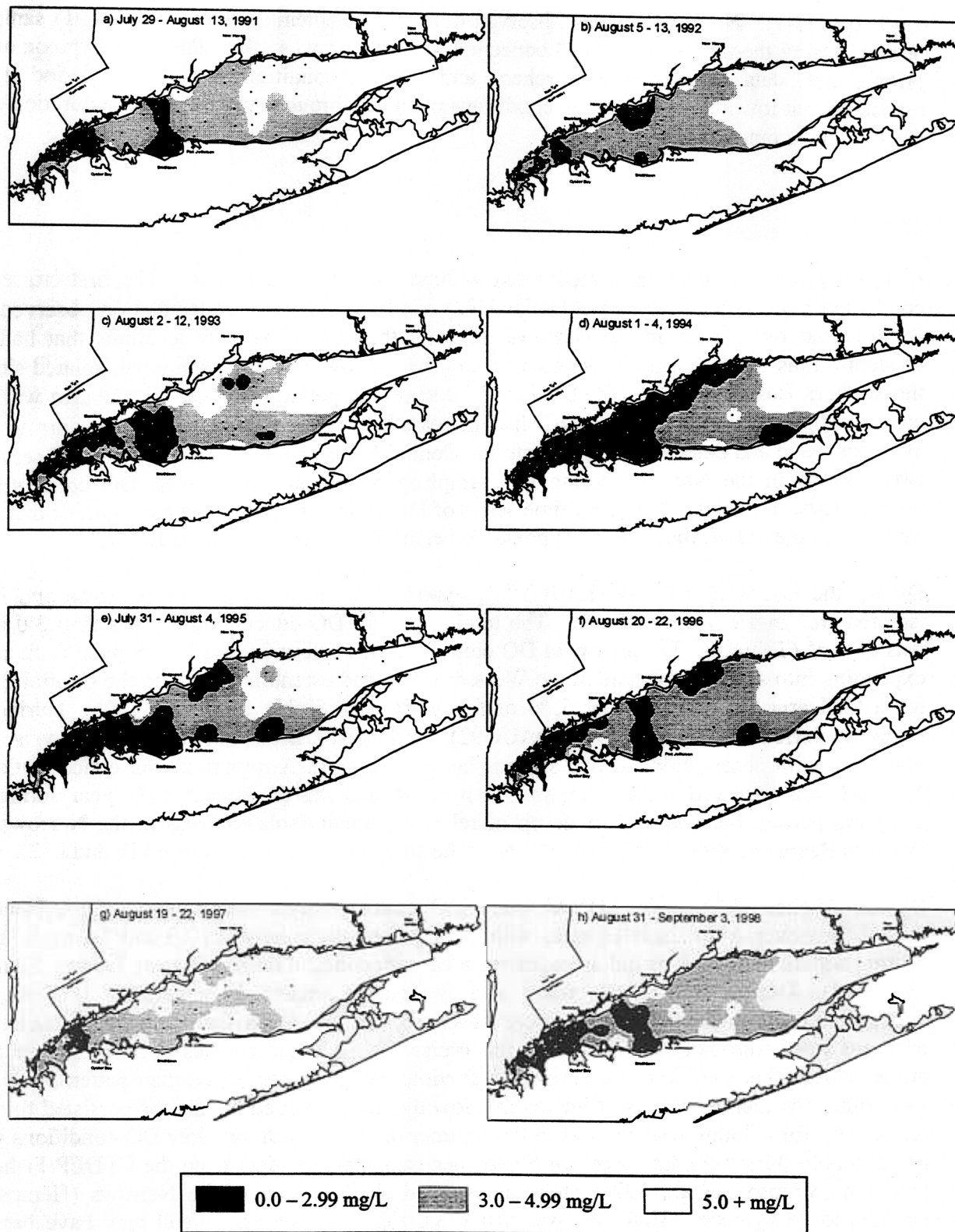
Hypoxia was observed at stations in western LIS during the second sampling period (WQAUG91, July 29 to August 13). Using the time series of DO concentrations at station A2 and weather conditions during this period, the onset of hypoxia was estimated to have begun on July 19. A continuous band of hypoxic bottom waters was observed through a large portion of the Narrows. An additional area in the Western Basin was also hypoxic (pp. C-1). The lowest DO concentrations observed all summer (1.4 - 1.6 mg/L) were observed on July 31 at 3 stations located in the Narrows and Western Basin. The total area affected by hypoxia during this period was 330 km<sup>2</sup>, the maximum area of hypoxia observed during the summer of 1991, and 12% of the study area (Table 5 and Figure 11a). The total area with DO concentrations below 5.0 mg/L was 1541 km<sup>2</sup>, over 56% of the study area (Table 5 and Figure 10a).

By the August 21-28 cruise (HYAUG91), hypoxia was limited to two deep water stations (22.7 and 37.6 meter depths) in the Western Basin, both with dissolved oxygen concentrations of 2.9

**Table 5.** Estimated area (square kilometers) of Long Island Sound affected by low dissolved oxygen in each of five 1.0 mg/L intervals during each cruise, 1991-1998\*

YEAR	Dissolved Oxygen Interval mg/L	Sampling Cruise						
		HYJUN	WQJUL	HYJUL	WQAUG	HYAUG	WQSEP	HYSEP
1991	0.0-0.99	No cruise	-	No cruise	-	-	-	No cruise
	1.0-1.99		-		93	-	-	
	2.0-2.99		-		237	16	-	
	3.0-3.99		353		630	259	NO AREA ESTIMATE	
	4.0-4.99		607		581	409	NO AREA ESTIMATE	
1992	0.0-0.99	-	-	-	-	-	-	No cruise
	1.0-1.99	-	3	2	19	-	-	
	2.0-2.99	-	14	69	205	20	-	
	3.0-3.99	NO AREA ESTIMATE	156	447	613	495	NO AREA ESTIMATE	
	4.0-4.99	NO AREA ESTIMATE	620	982	506	547	NO AREA ESTIMATE	
1993	0.0-0.99	-	3	-	-	-	-	No cruise
	1.0-1.99	-	7	-	23	-	-	
	2.0-2.99	-	25	14	495	126	-	
	3.0-3.99	-	265	193	711	365	NO AREA ESTIMATE	
	4.0-4.99	54	959	854	344	752	NO AREA ESTIMATE	
1994	0.0-0.99	-	-	-	73	-	-	-
	1.0-1.99	-	-	8	477	94	4	-
	2.0-2.99	-	100	248	472	260	85	-
	3.0-3.99	NO AREA ESTIMATE	397	1054	530	596	530	NO AREA ESTIMATE
	4.0-4.99	NO AREA ESTIMATE	952	545	295	489	840	NO AREA ESTIMATE
1995	0.0-0.99	-	-	-	48	-	-	No cruise
	1.0-1.99	-	-	-	135	-	-	
	2.0-2.99	-	-	111	607	2	-	
	3.0-3.99	-	24	241	554	821	9	
	4.0-4.99	19	624	1027	245	704	424	
1996	0.0-0.99	-	-	-	-	-	13	-
	1.0-1.99	-	-	-	-	70	79	-
	2.0-2.99	-	-	-	-	499	462	-
	3.0-3.99	NO AREA ESTIMATE	96	207	153	730	704	NO AREA ESTIMATE
	4.0-4.99	NO AREA ESTIMATE	570	540	1180	528	456	NO AREA ESTIMATE
1997	0.0-0.99	-	-	-	-	-	-	-
	1.0-1.99	-	-	-	-	6	-	-
	2.0-2.99	-	-	-	9	71	-	-
	3.0-3.99	-	12	63	223	210	NO AREA ESTIMATE	NO AREA ESTIMATE
	4.0-4.99	34	53	513	1330	630	NO AREA ESTIMATE	NO AREA ESTIMATE
1998	0.0-0.99	-	-	-	18	-	-	-
	1.0-1.99	-	-	-	92	21	90	-
	2.0-2.99	-	33	86	203	212	346	-
	3.0-3.99	NO AREA ESTIMATE	82	307	376	884	634	53
	4.0-4.99	NO AREA ESTIMATE	647	617	696	399	578	587

\* "-" indicates no observations within the associated DO interval (area = zero); shaded areas indicate the presence of hypoxia.



**Figure 11.** Maps of Long Island Sound showing areas affected by low dissolved oxygen concentrations during the peak hypoxic event (largest area with DO less than 3.0 mg/L) in each of the eight years 1991 through 1998.

mg/L (pp. C-1). No hypoxia was observed during the September 4-12 (WQSEP91) sampling period. Using the time series of DO concentrations at the two stations that were hypoxic on the prior cruise, data from other researchers, and weather conditions during this period it was estimated that low dissolved oxygen conditions persisted through August 28, for a duration of 41 days in the summer of 1991.

## 1992

In 1992 six cruises were conducted between June 29 and September 9. The first cruise was conducted from June 29 to July 2 (HYJUN92) and the lowest DO concentration observed was 3.9 mg/L at one station in the Narrows. During this cruise the only locations that had DO concentrations below 5.0 mg/L were an area in the Narrows and two additional isolated sites in the Western Basin (pp. C-2). By the July 7-20 sampling period (WQJUL92), the area with DO concentrations of less than 5.0 mg/L had increased, encompassing most of the Narrows and Western Basin and extending slightly into the Central Basin (pp. C-2). Hypoxia was observed at two stations in the Narrows during this sampling period, and the lowest DO concentration observed was 1.7 mg/L. Using the time series of DO concentrations at the two stations that were hypoxic on the cruise, the onset of hypoxia was estimated to have begun on July 7.

During the last week of July (HYJUL92), hypoxia was observed in the Narrows and in an isolated area in the Western Basin. The total area with DO concentrations less than 3.0 mg/L was 71 km<sup>2</sup> (Table 5). The area with DO concentrations below 5.0 mg/L continued to increase, expanding into shallower waters of the Western Basin and extending well into the Central Basin, for a total area of 1500 km<sup>2</sup>, or 55% of the study area (Table 5 and pp. C-2). During the sampling period of August 5-13 (WQAUG92), the lowest DO concentrations of the year were observed, with observations at two stations below 2.0 mg/L. A minimum DO concentration of 1.2 mg/L was observed in the Narrows. The hypoxic area was the largest of the year during this sampling period, but was still made up of relatively small, isolated areas in the Narrows and Western Basin encompassing 224 km<sup>2</sup>, 8% of the study area (Table 5, Figure 11b and C-2).

By the August 24-28 cruise (HYAUG92), DO concentrations had increased throughout the Sound. However, a few isolated areas with DO concentrations between 2.3 and 2.9 mg/L in the bottom waters remained, as did an extensive area with concentrations between 3.0 and 5.0 mg/L (pp. C-3). During a monthly water quality cruise conducted September 1-2, no DO concentrations less than 3.0 mg/L were observed, but the areas that remained hypoxic the previous week were not sampled during this cruise. Using the time series of DO concentrations at the stations that were hypoxic during the previous sampling period, weather patterns and data from other researchers, it was estimated that low dissolved oxygen conditions persisted through August 30, for a duration of 55 days in the summer of 1992. Although low DO conditions were not observed during the first week of September, supplemental data from the CTDEP Fisheries Division (Simpson et al., 1994) show an isolated shallow area in the Narrows (Hempstead Harbor) to be hypoxic. That area was above 3.0 mg/L on August 25 and may have become hypoxic for a short period of time in September because of weather patterns that influenced this shallow water station. In general, low dissolved oxygen conditions persisted in the Sound for a long period during the summer of 1992, but the area affected was not extensive.

In 1993 six cruises were conducted between June 28 and September 9. The first cruise was conducted from June 28 to July 2 (HYJUN93) and DO concentrations below 5.0 mg/L were limited to two small isolated areas, one in the Narrows and one in the Western Basin. During the next cruise (WQJUL93, July 7 -15) hypoxia was observed at three isolated, shallow (less than 20 meters) stations in the Narrows. The lowest DO concentration observed was 0.9 mg/L in the western Narrows. This was the earliest date that such a low DO concentration (less than 1.0 mg/L) was observed during this study. Using the time series of DO concentrations at the stations that were hypoxic on the cruise, data from other researchers, and weather conditions during this period, the onset of hypoxia was estimated to have begun on July 4. Besides the hypoxic conditions, the area having bottom DO concentrations between 3.0 and 5.0 mg/L was very widespread, extending through the Narrows and Western Basin and into the Central Basin (pp. C-4).

Although in the July 26-29 cruise (HYJUL93) the area of LIS below 5.0 mg/L increased eastward to include more of the Central Basin, all of the three locations in the Narrows that were hypoxic on the previous cruise showed increased bottom water DO concentrations. Three other locations in the Narrows had DO concentrations fall below 3.0 mg/L, so that hypoxia continued to affect small isolated areas. During the August 2-12 sampling period (WQAUG93), hypoxic conditions became widespread, extending through the Narrows, a significant portion of the Western Basin, and including some isolated areas in the Central Basin. The total area affected by hypoxia at this time was 518 km<sup>2</sup>, or 19% of the study area (Table 5, Figure 11c and pp. C-4). The minimum DO concentration observed was 1.8 mg/L in the Narrows. The area of dissolved oxygen concentrations below 5.0 mg/L increased to 1573 km<sup>2</sup>, 58% of the study area, having spread north and east in the Central Basin and into the southwest edge of the Eastern Basin.

By the August 17-26 cruise (HYAUG93), there had been an increase in DO concentrations throughout the Sound. Hypoxia was limited to a 126-km<sup>2</sup> area in the deep waters of the Western Basin, with DO concentrations ranging from 2.6-3.0 mg/L. A significant area, 1243 km<sup>2</sup>, extending through the Narrows and the Western and Central Basins, continued to exhibit DO concentrations below 5.0 mg/L. During the September 7-8 water quality cruise, hypoxia was recorded at stations B3 and D3 (both in the Narrows) with DO concentrations of 0.7 and 2.1 mg/L, respectively (pp. C-5). The DO concentration at station B3, 0.7 mg/L, was the lowest value recorded during 1993. No hypoxia was observed during the next monthly water quality cruise, conducted October 5-6. Using the time series of DO concentrations at the stations that were hypoxic on the previous cruise, data from other researchers and weather conditions during this period it was estimated that low DO conditions persisted through September 19, for a duration of 78 days in the summer of 1993. This was the latest end date and the longest duration of hypoxia during the eight years of this study.

## **1994**

In 1994 seven cruises were conducted from June 21 - September 8. During the first cruise, conducted June 21-23 (HYJUN94), dissolved oxygen concentrations below 5.0 mg/L were

observed in the Narrows and Western Basin (pp. C-6). The lowest value observed was 4.1 mg/L at Station 15 in the Western Basin. By the July 5-11 cruise (WQJUL94), DO concentrations had decreased throughout the Sound, and hypoxia was observed in isolated areas of the Narrows and the Western Basin. The area affected by hypoxia (approximately 100 km<sup>2</sup>) was split into widely scattered and relatively shallow (10.4-18.1 meters depth) areas. Using the time series of DO concentrations at the stations that were hypoxic on this cruise, data from other researchers and weather conditions during this period, it was estimated that the onset of hypoxia was July 1, which was the earliest of the eight years included in this survey. A large area with DO levels less than 5.0 mg/L (1448 km<sup>2</sup>) extended through the Narrows, the Western Basin, a significant portion of the Central Basin and into the southwest edge of the Eastern Basin (Table 5 and pp. C-6).

As July progressed, the hypoxic areas increased with the area affected by hypoxia during the July 20-22 cruise (HYJUL94) including a large portion of the Narrows and a small area in the deep water of the Western Basin. The total area below 3.0 mg/L had increased to 256 km<sup>2</sup> and the area less than or equal to 5.0 mg/L had also increased to 1850 km<sup>2</sup>. Station 02 in the Narrows had the lowest DO concentrations of the cruise at 1.9 mg/L.

During the August 1-4 cruise (WQAUG94), severe low DO conditions were observed in the Narrows and the Western Basin. Dissolved oxygen concentrations of between 0.6 and 0.9 mg/L were observed at five stations in the Narrows and Western Basin. Hypoxia was extensive and continuous throughout the Narrows, most of the Western Basin, well into the northern portion of the Central Basin, and even affected an area in the southwest portion of the Eastern Basin (Figure 11d and pp. C-6). This was the largest hypoxic area observed during this study, at 1022 km<sup>2</sup>, 37.5% of the study area (Table 5). The lowest DO concentration observed was 0.6 mg/L at station 15 in the Western Basin. By the August 16-18 cruise (HYAUG94), the area affected by hypoxia had decreased significantly, to 354 km<sup>2</sup>. Hypoxia was observed in the Narrows, and the Western and Central Basins, however these areas of hypoxia were now isolated. Dissolved oxygen concentrations had increased to above 3.0, and in some cases even above 5.0 mg/L in much of the area in the Western, Central, and Eastern Basins that had been hypoxic during the previous cruise (pp. C-7).

By the August 29 - September 1 cruise (WQSEP94) hypoxia was restricted to the Narrows. However, the area with DO concentrations between 3.0 and 5.0 mg/L had again increased in size to include again a large portion of the Central Basin. The lowest DO observed was 1.9 mg/L at station A2 in the Narrows. During the September 7-8 cruise (HYSEP94), no hypoxia was observed, and only one station sampled had a bottom DO concentration of 5.0 mg/L. Using the time series of DO concentrations at the stations that were hypoxic on the previous cruise, data from other researchers and weather conditions during this period, it was estimated that low dissolved oxygen conditions persisted through September 6, for a duration of 68 days for the summer of 1994.

During the summer of 1995, six cruises were conducted between June 22 and September 12. The first cruise was from June 22 – 27 (HYJUN95) and only one station in the Narrows had a bottom DO concentration below 5.0 mg/L, at 4.6 mg/L. During the July 6 - 11 cruise (WQJUL95) DO values below 5.0 mg/L were observed in the Narrows, Western Basin, and into the Central Basin, for a total area of 648 km<sup>2</sup>, but no hypoxia was observed. A week later, during the July 18 - 20 cruise (HYJUL95), the first DO concentrations below 3.0 mg/L were documented in the Narrows, with a total hypoxic area of 111 km<sup>2</sup> (Table 5 and pp. C-8). The area with bottom DO concentrations less than or equal to 5.0 mg/L had also increased, to 1379 km<sup>2</sup>, expanding further into the Western and Central Basins, and extending into the southwestern edge of the Eastern Basin. Using the time series of DO concentrations at the hypoxic stations, data from Interstate Sanitation Commission (ISC 1996), and weather conditions during this period, the onset of hypoxia was estimated to have begun on July 12.

During the cruise conducted July 31 - August 4 (WQAUG95), hypoxia was widespread (Figure 10e and pp. C-8). Hypoxic conditions extended continuously through the Narrows and much of the Western Basin, and were additionally observed in three isolated areas in the Central Basin, for an estimated area of 790 km<sup>2</sup>, or 29% of the study area (Table 5 and Figure 11e). Dissolved oxygen concentrations below 1.0 mg/L were observed at stations A4 and B3 in the Narrows, with concentrations of 0.8 and 0.9 mg/L, respectively. Severe low dissolved oxygen conditions (1.0-1.9 mg/L) were observed at four additional stations in the Narrows and the Western Basin.

By the August 14-16 cruise (HYAUG95), hypoxia was limited to a single station (A4) in the western Narrows, but the area with DO concentrations below 5.0 mg/L continued to be extensive, at 1545 km<sup>2</sup>, almost 57% of the study area (Table 5 and pp. C-9). During the cruise conducted September 5-12 (WQSEP95), no hypoxia was observed in LIS. Using the time series of dissolved oxygen concentrations at station A4 (the only station hypoxic during the August 14-16 cruise) and the weather conditions favorable to the breakup of hypoxia created by Hurricane Bertha, it was estimated that low dissolved oxygen conditions persisted through August 15, for a duration of 35 days in the summer of 1995.

## **1996**

In 1996, seven cruises were conducted from June 25 through September 20. During the first cruise conducted from June 25-27 (HYJUN96), the minimum dissolved oxygen concentration was 3.1 mg/L observed at Station 02 in the Narrows. During the July 8-11 cruise (WQJUL96), the DO concentrations in the Narrows were similar to those recorded during the prior cruise. In addition, isolated locations in the Western and Central Basins had decreased to 5.0 mg/L or less, increasing the total area less than 5.0 mg/L to approximately 666 km<sup>2</sup> (Table 5 and pp. C-10). By the July 22-25 cruise (HYJUL96), the area below 5.0 mg/L increased slightly (747 km<sup>2</sup>), so that this area was continuous through the Narrows and Western Basin and into the Central Basin. No hypoxia was observed (pp. C-10).

By the August 5-8 cruise (WQAUG96), the area with dissolved oxygen concentrations of 5.0 mg/L or less had expanded into more of the Central Basin, and into the Eastern Basin. Although the size of the area affected by DO concentrations of 5.0 mg/L or less was extensive at 1333 km<sup>2</sup> (49% of the study area) no hypoxia was observed (Table 5 and pp. C-10). The lowest DO observed was 3.4 mg/L. This was the only summer during the eight-year period (1991-1998) that hypoxia was not observed by the first week of August. Typically, early August was the period when maximum areas were affected by hypoxia.

By the August 20-22 cruise (HYAUG96), hypoxic conditions had developed through the Narrows and part of the Western and Central Basins, with a total area with DO concentrations of 3.0 mg/L or less of 569 km<sup>2</sup>, or 21% of the study area (Table 5, Figure 11f and pp. C-11). Dissolved oxygen concentrations in the Narrows and Western Basin dropped to levels below 2.0 mg/L at six stations (A4, A5-ISC, B3, E1, 12, and 14). Using the time series of DO concentrations at the stations that had DO concentrations below 3.0 mg/L, the hot and humid weather patterns during and prior to this period, and observations made by other researchers (Simpson et al 1997 and ISC 1997), the onset of hypoxia was estimated to have begun on August 10, which was the latest estimated onset date in the eight-year period.

By the September 3-6 cruise (WQSEP96), the area with dissolved oxygen concentrations of 3.0 mg/L or less (554 km<sup>2</sup>), was similar to that observed during the previous cruise, although some very severe low DO concentrations, less than 1.0 mg/L, were observed where there had been none previously (Table 5). There were no longer any hypoxic areas observed in the Central Basin, but hypoxia persisted in the Narrows and Western Basin (pp. C-11). Dissolved oxygen concentrations had increased above 3.0 mg/L at some stations (12, E1, H2, and 31), but had decreased at other stations, dropping below 1.0 mg/L at stations A4, B3, and 02 in the Narrows. During the September 20 cruise (HYSEP96) all stations that were significantly below 3.0 mg/L during the prior cruise were sampled and all had DO values above 5.6 mg/L. Using the time series of DO concentrations at the stations sampled during the September 20 cruise, data from the Interstate Sanitation Commission's September 9 and 16 cruises (ISC 1997), and weather conditions during this period, it was estimated that hypoxic conditions persisted through September 12, for a duration of 34 days in the summer of 1996.

## **1997**

During the summer of 1997, seven cruises were conducted between June 27 and September 17. The first cruise was conducted from June 27 – 30 (HYJUN97) and only three stations had DO levels below 5.0 mg/L (A4, B3, and 15, with 4.6, 4.8 and 4.8 mg/L respectively). The next sampling cruise was conducted July 8-9 (WQJUL97) and the conditions observed were similar to the previous cruise. The lowest observation was at station A4, which had a DO concentration of 3.7 mg/L. Only three additional stations (B3, 01, and 02) had concentrations below 5.0 mg/L.

By the July 22-24 cruise (HYJUL97) the area of LIS that had DO levels below 5.0 mg/L had increased to 576 km<sup>2</sup> in the Narrows, Western Basin and Station 22 in the Central Basin (Table 5 and pp. C-12). Although DO concentrations less than 5.0 mg/L became prevalent, no areas fell below 3.0 mg/L. The lowest DO concentration observed was 3.0 mg/L at Station A5 sampled by

ISC. Two CTDEP stations, A4 and B3, had similar concentrations, with 3.2 and 3.1 mg/L respectively.

Hypoxia was first observed during the August 4-7 cruise (WQAUG97) at station A4, with a DO concentration of 2.5 mg/L. It was estimated from the DO time series from station A4, supplementary data from Interstate Sanitation Commission (ISC 1998), and the hot/still weather patterns during and prior to this period, that the onset of hypoxia probably had occurred on July 26. In addition to the hypoxic area, the area that had DO concentrations less than 5.0 mg/L increased significantly in size to encompass more than 1562 km<sup>2</sup>, or over 57% of the study area (Table 5 and pp. C-12). By the August 19-22 cruise (HYAUG97), the hypoxic area had increased to 77 km<sup>2</sup>, or less than 3% of the study area (Table 5, Figure 11g and pp. C-13). The DO concentration at station A4, previously hypoxic, had increased to 4.3 mg/L, but six other stations (B3, 01, 02, C1, B2-ISC and H-B-ISC) had experienced a decline in DO and were hypoxic. Station 02 had the lowest oxygen concentration (1.9 mg/L) for the cruise and for the year. In contrast to the increase in hypoxic area, the area less than 5.0 mg/L decreased to 917 km<sup>2</sup>.

During the September 2-5 cruise (WQSEP97), hypoxia was observed at only two stations in the Narrows, A4 and 02, with DO concentrations of 2.3 and 2.5 mg/L respectively. There was not sufficient coverage in the Narrows to permit an acceptable area estimate. By the September 17 cruise (HYSEP97), no hypoxia was observed in Long Island Sound and the area with DO concentrations below 5.0 mg/L was confined to the Narrows. Using DO time series from stations A4 and 02, supplementary data from Interstate Sanitation Commission (ISC 1998), and the weather patterns during and prior to this period, it was estimated that hypoxia ended on September 12, for a duration of 48 days during the summer of 1997.

## **1998**

In 1998, seven cruises were conducted between June 24 and September 17. The first cruise was conducted from June 24 - 26 (HYJUN98) and only four stations in the Narrows had DO concentrations below 5.0 mg/L (A4, B3, 02, and C1). The next sampling cruise was conducted from July 6-9 (WQJUL98) and hypoxic conditions were present at four stations in the Narrows (A4, 02, 04 and B4-ISC). It was estimated that the onset of hypoxia in Long Island Sound occurred on July 5. The hypoxic area was estimated at 33 km<sup>2</sup> and the area of DO concentration less than 5.0 mg/L was 762 km<sup>2</sup> (Table 5 and pp. C-14).

Observations made during the July 21-23 cruise (HYJUL98) showed the area of bottom waters with DO concentrations under 5.0 mg/L had increased to 1010 km<sup>2</sup>, while the hypoxic area had increased to 86 km<sup>2</sup> (Table 5 and pp. C-14). The hypoxic area in the Narrows had persisted and an additional isolated location in the Western Basin (station 15) was also hypoxic. By the August 3-6 cruise (WQAUG98), DO conditions had worsened in the Sound. Two stations, A4 in the Narrows and 09 in the Western Basin had very severe low DO concentrations. The bottom water DO concentration at station A4 was 0.3 mg/L, which was the lowest concentration observed during this eight-year survey. Station 09 had a DO level of 1.0 mg/L in the bottom waters. Additional areas in the Western Basin were also hypoxic during this cruise. The total

hypoxic area encompassed 313 km<sup>2</sup> (11.5% of the study area) and the area of DO concentrations below 5.0 mg/L increased to 1385 km<sup>2</sup> (51%) (Table 5 and pp. C-14). Although the maximum hypoxic area for the year occurred later (see below), the maximum area observed with DO less than 1.0 mg/L and the maximum area with DO less than 2.0 mg/L both occurred during this cruise (Table 5).

By the August 17-21 cruise (HYAUG98) the overall DO conditions in the Sound had improved. No stations were observed with severe conditions and the hypoxic area decreased slightly to 233 km<sup>2</sup> (Table 5 and pp. C-15). The area of the Sound with DO concentrations below 5.0 mg/L had increased somewhat to 1516 km<sup>2</sup>. Although DO concentrations had increased at most stations in the Narrows and Western Basin, DO concentrations had decreased at most stations in the Central and Eastern Basins.

By the next cruise, August 31 - September 3 (WQSEP98), DO conditions had worsened again. The hypoxic area increased to the maximum for the year at 436 km<sup>2</sup> (16% of the study area), as did the area below 5.0 mg/L, which increased to 1648 km<sup>2</sup> (60.5%) (Table 5 and Figure 11h). 1998 had the latest maximum hypoxic area (during the WQSEP98 cruise) of all eight years (Table 5). Conditions improved greatly by the next sampling cruise (HYSEP98, September 15-17). No stations were hypoxic and the lowest DO concentration observed was 3.1 mg/L at station A4 in the Narrows. Although there were no hypoxic areas, the area with DO concentrations under 5.0 mg/L still encompassed 640 km<sup>2</sup>. Using the time series of the stations that were hypoxic on the previous cruise, it was estimated that hypoxic conditions in LIS persisted until September 15. Therefore, the duration of hypoxia in the Sound was estimated at 73 days for the summer of 1998.

### *Trends in Timing and Duration of Hypoxia*

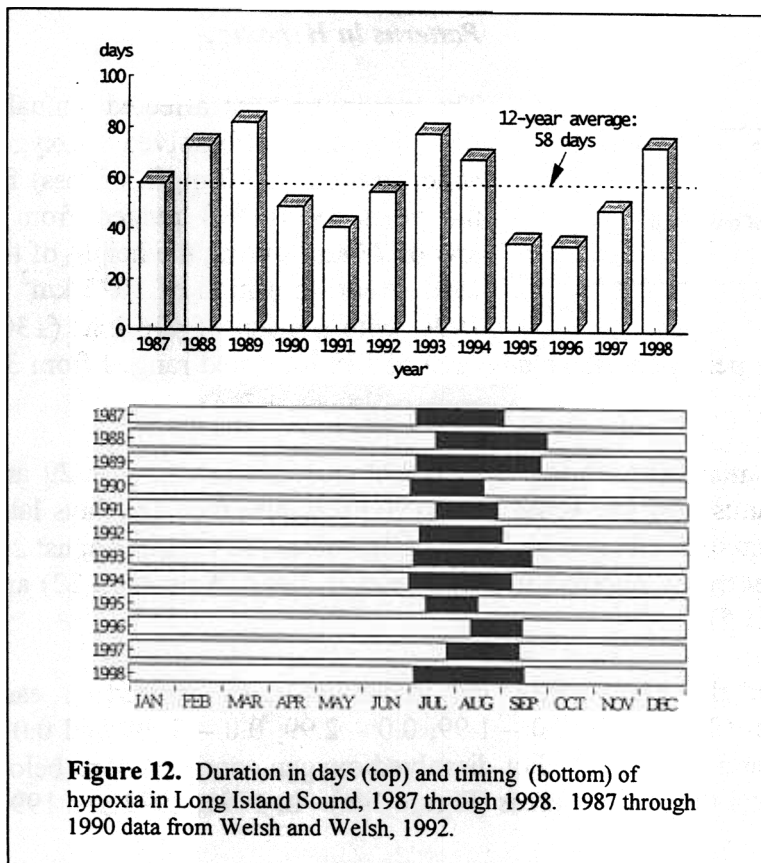
The estimated start date of hypoxia in LIS over the eight years, 1991-1998, ranged from July 1 (Julian date 182) in 1994, to August 10 (Julian date 223) in 1996, a difference of 41 days (Table 6 and Figure 12). The mean start date was July 15(±14 days). The end date of hypoxia also varied annually, ranging from August 15 in 1995, to September 19 in 1993 (a difference of 36 days). The mean end date was September 6(±12 days).

The duration of hypoxia also varied annually, from the shortest duration in 1996 of 34 days, to the longest duration in 1993 of 78 days (Table 6 and Figure 12). The average duration over the eight years was 54 days (±17 days).

These results were compared with previous studies of hypoxia in Long Island Sound from 1987 - 1990 (Welsh and Welsh, 1992) (Table 7). The earlier studies generally show estimated start and end dates of hypoxia within the range seen in the current study. The exceptions are that two years (1988 and 1989) had later end dates, extending the latest observed end date to September 30 in 1988. The 82-day duration of hypoxia observed in 1989 was longer than any observed through 1998.

**Table 6.** Estimates of area and duration of hypoxia (dissolved oxygen concentrations less than 3.0 mg/L) in Long Island Sound 1991-1998.

Year		Estimated Start Date	Estimated End Date	Maximum Area (km <sup>2</sup> )	Percent of Study Area	Duration (days)
1991	Calendar date	July 19	August 28	330	12.1	41
	Julian date	200	240			
1992	Calendar date	July 7	August 30	224	8.2	55
	Julian date	189	243			
1993	Calendar date	July 4	September 19	518	19.0	78
	Julian date	185	262			
1994	Calendar date	July 1	September 6	1022	37.5	68
	Julian date	182	249			
1995	Calendar date	July 12	August 15	790	29.0	35
	Julian date	193	227			
1996	Calendar date	August 10	September 12	569	20.9	34
	Julian date	223	256			
1997	Calendar date	July 27	September 12	77	2.8	48
	Julian date	208	255			
1998	Calendar date	July 5	September 15	436	16.0	73
	Julian date	186	258			
<b>1991-1998 Mean <math>\pm</math>SD</b>	Calendar date	<b>July 15</b>	<b>September 6</b>	<b>496 <math>\pm</math>305</b>	<b>18.2 <math>\pm</math>11</b>	<b>54 <math>\pm</math>17</b>
	Julian date	<b>196 <math>\pm</math>14 days</b>	<b>249 <math>\pm</math>12 days</b>			



**Figure 12.** Duration in days (top) and timing (bottom) of hypoxia in Long Island Sound, 1987 through 1998. 1987 through 1990 data from Welsh and Welsh, 1992.

If all twelve years of data are considered (1987-1998), hypoxia has been observed from as early as July 1 in 1994 (the earliest estimated onset) to as late as September 30 in 1988 (the latest estimated end date). The average duration over all twelve years was 58 days with a standard deviation of 17 days.

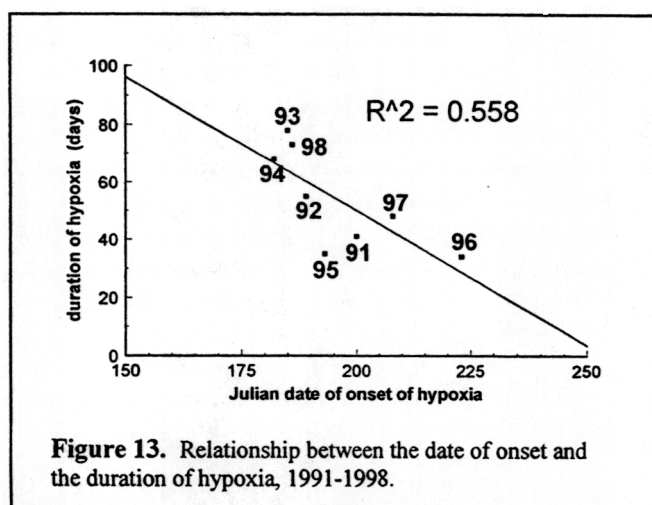
There appeared to be a cyclic pattern to the duration data, with peaks occurring in 1988-1989, 1993-1994, and again in 1998 (Figure 12). Also apparent from the data was a relationship between the date of onset of hypoxia and the duration. Clearly, the

**Table 7.** Estimates of duration of hypoxia (dissolved oxygen concentrations less than or equal to 3.0 mg/L) in Long Island Sound 1987-1990. Data from Welsh and Welsh, 1992.

Year		Estimated Start	Estimated End	Duration (days)
1987	Calendar date	July 6	September 1	58
	Julian date	187	244	
1988	Calendar date	July 18	September 30	73
	Julian date	200	273	
1989	Calendar date	July 6	September 25	82
	Julian date	187	268	
1990	Calendar date	July 2	August 20	49
	Julian date	183	232	
<b>1987-1990 Mean <math>\pm</math>SD</b>	Calendar date	<b>July 8</b>	<b>September 11</b>	<b>65 <math>\pm</math>15</b>
	Julian date	<b>189 <math>\pm</math> 7 days</b>	<b>254 <math>\pm</math>19 days</b>	

potential for a longer duration existed when the date of onset was early. In fact, the data show that the earlier hypoxia developed in the Sound, the more likely it was that the duration would be long (Figure 13). The three years with the earliest onset dates (1993, 1994 and 1998) were also the years with the

longest duration of hypoxia (Table 6). 1996 had the latest onset date (August 10) and the shortest duration (34 days) (Table 6).



**Figure 13.** Relationship between the date of onset and the duration of hypoxia, 1991-1998.

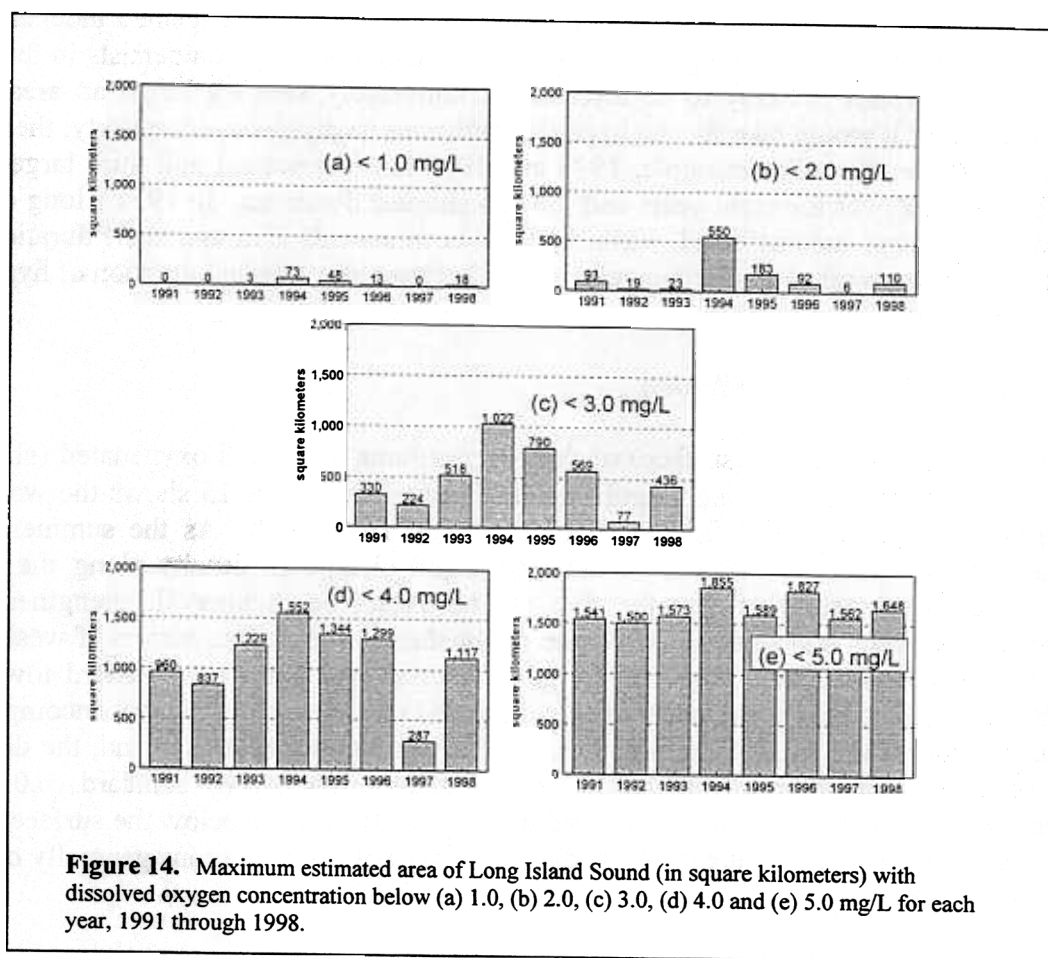
### *Patterns in Hypoxic Area*

The maximum area affected annually by hypoxia (dissolved oxygen concentration of 3.0 mg/L or less) for the years 1991-1998 ranged from a low of 77 km<sup>2</sup> during the height of the 1997 event, to a high of 1022 km<sup>2</sup> in 1994, with a mean of 496 km<sup>2</sup> ( $\pm$ 305

km<sup>2</sup>) (Table 6 and Figure 14c). The percent of the study area of LIS impacted ranged from 3 - 38% with a mean of 18% (Table 6).

From 1991 through 1995, the maximum area of hypoxia was observed between July 29 and August 13 (Table 5). In 1996, an unusually late onset of hypoxia was observed (22 days later than any other year) and the maximum area affected by hypoxia was observed during August 20-22. The timing of the peak area affected by hypoxia was also later in 1997 (August 19-22) and 1998 (August 31-September 3) (Table 5).

To compare hypoxia severity over the eight years, the maximum area affected in each cumulative dissolved oxygen interval (0.0 - 0.99, 0.0 - 1.99, 0.0 - 2.99, 0.0 - 3.99, and 0.0 - 4.99 mg/L) was calculated (Table 5 and Figure 14). For dissolved oxygen concentrations below 1.0 mg/L, the years 1994 and 1995 had the greatest areas (Figure 14a). In 1991, 1992 and 1997,



no dissolved oxygen concentrations less than 1.0 mg/L were observed. In 1993, observations from two different cruises each produced a single station with a dissolved oxygen value less than 1.0 mg/L. For the WQJUL93 cruise, this resulted in an area estimate of three square kilometers; no area estimate was calculated for the HYSEP93 cruise due to insufficient coverage.

Dissolved oxygen concentrations less than 2.0 mg/L were observed each year of this study. The area impacted in 1994 (550 km<sup>2</sup>) in the 0-2.0 mg/L oxygen interval was significantly larger than any other year. The maximum area impacted by DO concentrations less than 2.0 mg/L during the other seven years ranged from 6 - 183 km<sup>2</sup> (Table 5 and Figure 14b).

Some of the differences observed in the area estimates may be attributed to the changes in sampling design (*i.e.*, mostly random site sampling with some fixed stations from 1991-1993 and all fixed station sampling from 1994-1998) and sampling schedule (Table 4), although station coverage by basin and depth strata were similar between the two designs. Additionally, conditions changed rapidly during the summer months, so that results from two consecutive cruises (generally with two weeks between them) could be quite different. It is possible that a peak hypoxic event was not observed as a result of the semi-weekly sampling schedule.

Hypoxic area maxima and duration were not correlated ( $R^2=0.012$ ) and seemed independent of each other. While it might seem logical to assume that the longer hypoxia persists in the Sound the greater an area that is likely to be affected, or conversely, that the larger an area that is affected, the longer it would take for the hypoxic conditions to disappear completely, the data do not show this to be true. For example, 1995 and 1996 had the second and third largest areas affected by hypoxia over the eight years and the two shortest durations. In 1994 a long duration combined with a large area affected, while in 1991 both a small area and short duration were observed. The data revealed no obvious relationship between the area and duration of hypoxia.

### ***Vertical Dissolved Oxygen Distribution***

Generally, the first five meters (surface) of the water column were well oxygenated (above 5.0 mg/L) throughout the year in Long Island Sound (Figure 15). Figure 15 shows the worst case condition (peak hypoxic event) from each of the years 1994-1998. As the summer season approached, the pycnocline (location of the most rapid change in density along the density gradient), generally located between the five and ten meter depth interval, strengthened and lower dissolved oxygen concentrations became established in the bottom waters of western and central LIS. The area of low dissolved oxygen increased and extended eastward toward the Central Basin of LIS. This water mass of low dissolved oxygen concentrations encompassed a significant portion of the axial volume of LIS. In the western and central Sound, the dissolved oxygen concentrations progressively fell below the state water quality standard (6.0 mg/L). There was an eastward push of lower dissolved oxygen concentrations below the surface waters. As late summer approached a retreat of low dissolved oxygen concentrations generally occurred as stratification weakened.

### ***Stratification***

Stratification, the density difference between the surface and bottom waters, influenced dissolved oxygen concentrations in the bottom waters of Long Island Sound. The density stratification of the water column creates a barrier between the surface and bottom waters, and it is this barrier, the pycnocline (where the change in density with depth is at its greatest), that prevents mixing between the layers. Both temperature and salinity differences between the surface and bottom waters can contribute to the density gradient. The temperature gradient (thermocline) develops with warmer, lighter water on top and cooler heavier water on the bottom. The salinity gradient (halocline) develops with less saline, lighter water on top and more saline, heavier water on the bottom. In Long Island Sound it is the difference in temperature (the thermal gradient or thermocline) that accounts for most of the difference in density from the surface to the bottom. Long Island Sound is a thermally stratified estuary. The more rapid the change in temperature with depth, the stronger a barrier the thermocline presents to mixing of the water column.

Surface and bottom water temperatures were influenced by many natural factors including:

- timing and the amount of precipitation
- air temperatures
- weather patterns (both short and long term)